Packaging for Spacecraft and Its Commercial Implications

by:

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Introduction

As spacecraft continue to become more compact, Micorelectromechanical Systems (MEMS) offer a unique opportunity to achieve enhanced performance while lowering mass, volume and power requirements of scientific instruments and spacecraft functions. With opportunity comes challenge and MEMS are no exception. One particular area of challenge is the packaging of MEMS.

This paper discusses aspects of electronic packaging which are critical to MEMS devices and in particular, of extreme importance to packaging devices which are intended for use aboard spacecraft. The **ultra-low volume fabrication of space** application devices dictates packaging and **QA** methodologies that provide a thorough process of validation, proof of process build and problem detection by inspection. Examples of these methodologies are presented along with implications as to how the identification of failure mechanisms and paths to improvement can benefit the MEMS industry.

Background

Scientific American devoted its 150th anniversary issue in September 1995 to a forecast of the "Key Technologies for the 21st Century". Prominent among these technologies were MEMS. Some of the devices which have been or are being developed for commercial applications include; implantable strain gauges, micro surgery instruments for cataract removal and insertion of replacement intraocular lenses, micro gyroscopes, accelerometers for collision detection and airbag deployment, chemical sensors, tactile sensors (robot skin), pressure sensors, micro valves, microthrusters, micro spectrometers, micro relays, micro, refrigerators, and micro dew point sensors.

In the simplest terms, MEMS are sensors and machines fabricated using microelectronics technology (photomasks, etching, vapor deposition, etc.). These microsensors can be made which respond to almost any imaginable stimuli, light, heat, pressure, acceleration and many more. Micromachines achieve motion by use of magnetic, piezoelectric, capacitive and other forces.

NASA's Jet Propulsion Laboratory (JPL) has MEMS programs which it is pursuing on several levels. In addition to having an in-house fabrication facility producing a **wide variety of MEMS devices, JPL is also** working closely with numerous other facilities, academic, government and commercial to develop MEMS devices which may be used in future space applications.

Packaging Studies

One important contribution area for the successful integration of microelectronics into spacecraft has been the qualification of advanced packaging types for use in spaceflight. JPL has been conducting a series of studies on the reliability of various forms of microelectronics packaging. This work began with a study of the reliability of j-lead and gull wing flat packs.

The flat pack study was followed by work (which continues) on the reliability of

several types of Ball Grid Array packages. This latter study was facilitated by the formation of a large consortium participated in by many of the leading suppliers and users of ball grid arrays. The size of the consortium made possible an extensive Design of Experiments reliability study including numerous critical parameters such as board material, package material, number of balls per package, solder paste quantity, pad placement, etc. This study has successfully demonstrated that Ball Grid Arrays can be selected for many spaceflight missions with a high degree of confidence in their reliability.

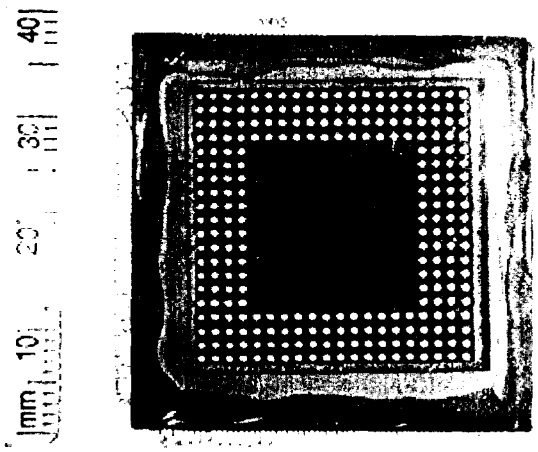

Fig 1. *Difference in Mounting Area for the Same I/O BGA and QFP Packages*

The study was also of considerable value to the other members of the consortium who participated because of their interest in the commercial application of the technology. While for the most part, commercial products do not face all of the rigors of space, products such as cellular phones, pagers and automotive and aircraft electronics are required to operate reliably in a variety of harsh environments. Even such devices as video recorders are expected by the consumer to work whether in a desert at tern peratu res above 40 degrees C or in a Minnesota winter at minus 30 degrees C.

The success of the Ball Grid Array study has led to additional packaging reliability studies at JPL which are in their early stages. These include Direct Chip Attach and Micro Ball Grid Arrays. As in the previous study, JPL has begun to form a consortium of interested participants.

One of the keys to successful use of MEMS in spaceflight applications is understanding of the requirements for successfully packaging these devices for spaceflight. JPL is able to draw upon its wealth of knowledge of spaceflight requirements from its many years of experience in building and launching deep space probes. Assurance does not permit proof of process as do commercial or military production. The goal is to develop coherent design and qualification methodologies and apply that knowledge to identifying the critical parameters, methods and tools to package MEMS.

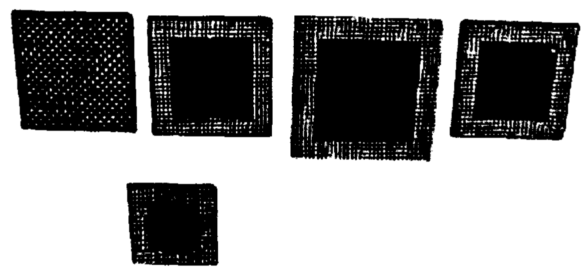

Fig 2. *Typical BGA Packages*

Challenges in Packaging MEMS

An electronic package serves two primary purposes. It provides both support and protection to the components which make up the electronic circuit. Packaging must also allow for input and output of electrical signals. In certain cases, such as photo diodes, packaging may also be required to provide an access path for other types of stimulus such as optical, acoustic, pressure etc.

When the packaging of MEMS devices as sensors is considered, access of stimulus takes on added importance and complexity. MEMS sensors have been made which run the gambit of sensing capabilities including electromagnetic (across the entire optical spectrum from ultraviolet to IR up to '20 microns), acoustic, pressure, temperature, vibration, magnetic and many **more. In each case, once the device** is designed and fabrication techniques are developed, the packaging becomes a separate problem unique to the specific device.

Ordinary microelectronic devices require extreme standards of cleanliness during fabrication. After fabrication is complete, cleanliness standards required for packaging are typically far less critical. Only gross contaminants which might short a circuit, lead to corrosive reactions or in some other manner interfere with the functioning of the circuit are considered a problem. Cleanliness requirements for MEMS devices in packaging present a far more stringent set of requirements.

Because a MEMS device has moving parts on a microscopic scale, consideration must be given to the size of contaminant that would interfere with the motion of the various components of the device. A small piece of dust or fragment of bonding wire less than a micron in length and diameter will, if in a critical spot, completely prevent the operation of a MEMS device. Worse yet, it may initially allow operation, but later move under environmental stresses so that **the** device develops a failure.

In order to increase the reliability of these and other MEMS devices, JPL is studying the use of novel techniques for the detection of various types of contaminants and other imperfections. In the case of contaminants, the usefulness of X-ray microimaging has been demonstrated for detecting contaminants trapped between the moving segments of the MEMS device. With proper use, the technique can also detect cracks and other defects in the device, which are invisible to optical microscopy.

An X-ray micro image of a tunneling hydrophore is shown in Figure 3. Although relatively difficult to image at low magnifications due to excessive X-ray transmission, high magnifications allowed for close inspection. A profile (top) and isometric (bottom) inspection of the cantilever bridge, which is silicon diffusion bonded to the lower sensing wafer, identified regions of un-bonded silicon (arrow A). While rather benign to the

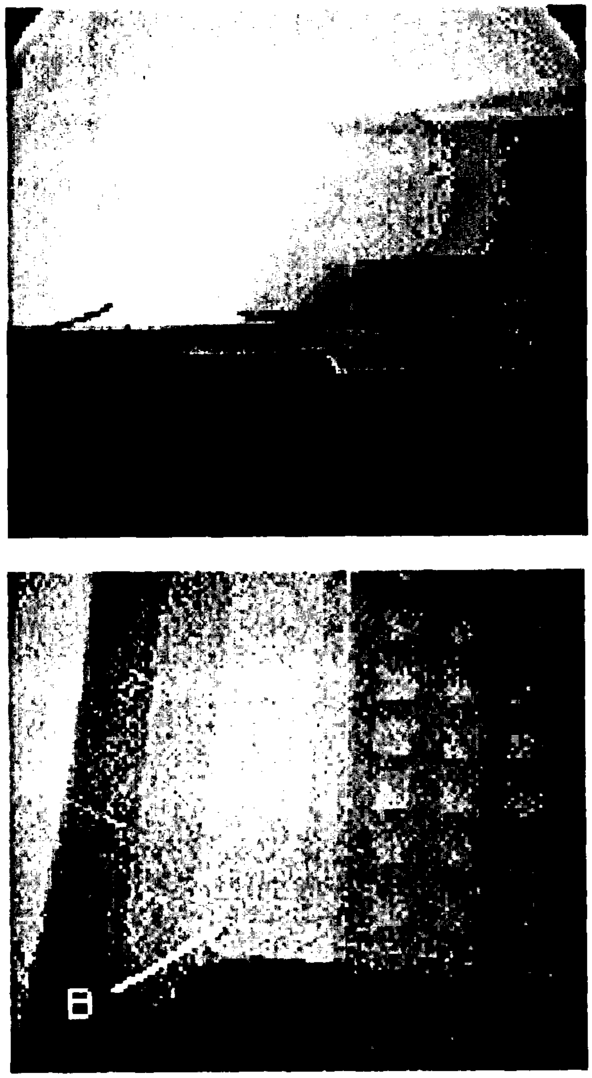

Fig 3. *Micro focus X-ray profile (top) and isometric (bottom) images of hydrophore cantilever bridge.*

operation of the device, this region could pose further problems associated with crack initiation in the cantilever bridge (arrow B) during excessive vibration. Isometric inspection of the same cantilever bridge noted the presence of a crack running through the thickness of the silicon wafer which was partially obscured by the gold plating of the parts.

Since many MEMS devices are formed from multiple components that are bonded together, another consideration is how to detect the completeness of the bond. Here, acoustic microscopy techniques have been found to be useful. These techniques can also show irregularities in thin layers that would otherwise be undetectable.

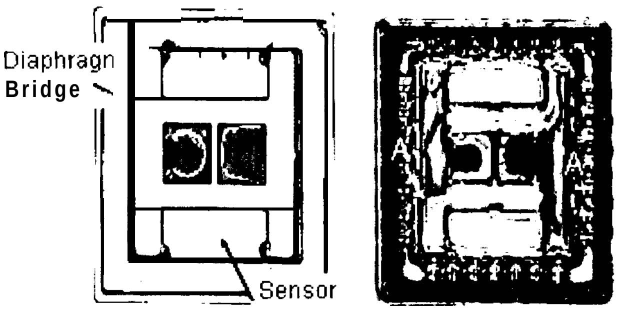

Fig 4. Acoustic Microscopy Image of Tunneling Accelerometer. Regions Defined by "A" Denote Lack of Compliance of Diaphragm Bridge to Sensor Wafer.

Example: STRV2 - The Maple Experiment

During the first year of a planned three year study, the Code Q projects addressed problems associated with the fabrication and packaging of a Quantum Tunneling Accelerometer to be used as a flight experiment on STRV2. Valuable lessons were learned concerning the necessity of materials qualification and control, process monitoring and designing for manufacturability. This knowledge will be applied to help assure the success of the MEMS technology demonstrations which will be flying on several of the New Millennium missions.

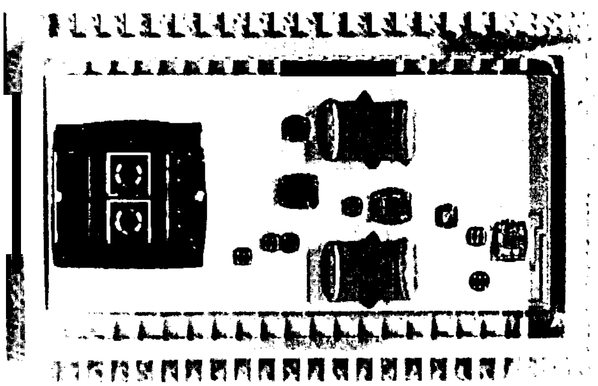

Fig 5. Custom Design for STRV2 MEMS Accelerometer

One area of study has been related to the unique contamination requirements of devices which make use of electron tunneling. These devices utilize a sharpened tip only 30 microns high which is spaced to within 10 Angstroms of a conductive surface. Electron tunneling takes place from a single high point on the **tip surface. Even adsorbed** molecules of water or organic compounds can lead to an unreliable tunneling effect. Because of this, out gassing from adhesives or other organic materials used in processing is critical to eliminate.

NASA has a wealth of data from measuring the outgassing of adhesives, coatings and other organic materials. This information can be found in NASA Reference Publication 1124 published by the Goddard Space Center. This publication is revised continuously as new materials are tested. Access of this information is now made easier by its availability on the internet at www.gsfc.nasa.gov.

Adsorbed contaminants require the use of spectroscopic techniques to detect their presence. JPL has demonstrated that XPS (X-ray photoelectric spectroscopy) can provide a useful method of detecting and identifying contaminants present on MEMS tunneling device components.

Example: The Hubble Telescope

The CCDs (Charge Coupled Device image detectors) on the Hubble telescope and Cassini spacecraft while not MEMS, presented a similar set of packaging challenges (coupling optical stimulus with electronic circuitry) with lessons learned which are valuable in the fabrication of MEMS instruments.

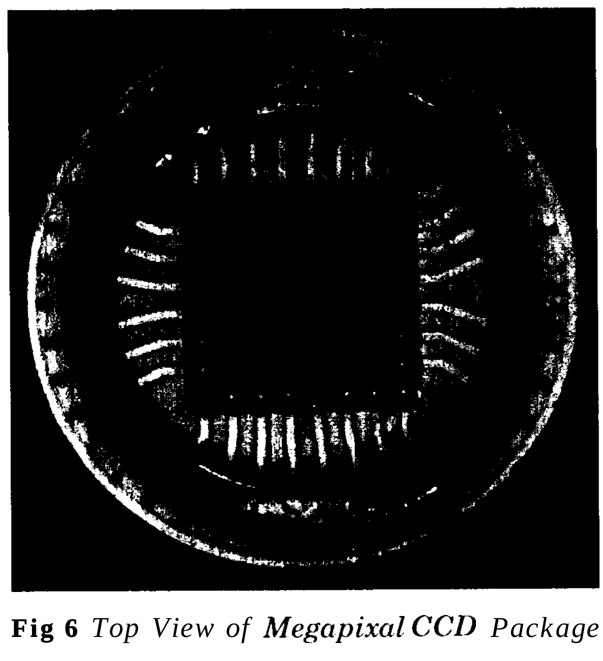

Fig 6 *Top View of Megapixal CCD Package*

Because the Hubble CCD devices see temperature excursions from -90°C, to +50°C compensating for coefficient of expansion mismatches was of great importance. The silicon chips (coefficient of thermal expansion $3x10^{-6}$) were bonded to alumina substrates chips (coefficient of thermal expansion $6x10^{-6}$) as in conventional microelectronic packages. Unlike conventional microelectronics, the body of the package was machined from Invar, a material with a thermal expansion coefficient of only $1.5x\ 10^{-6}$.

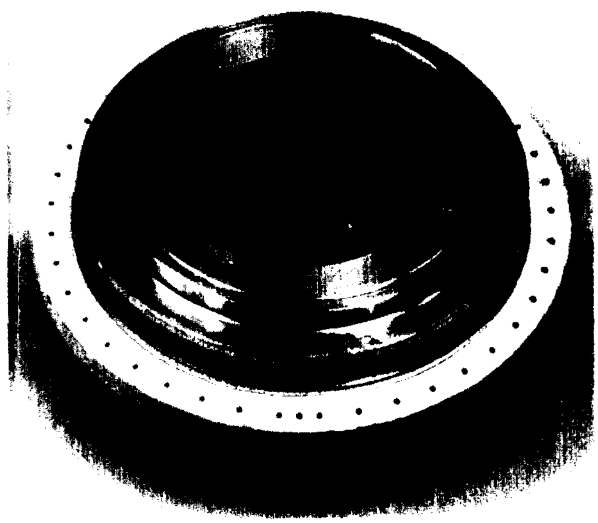

***Fig* 7** *Side View of Megapixal CCD Package*

This arrangement minimized changes in the focal position of the CCD, a critical consideration in this precision optical instrument.

Because this is a precision optical device, special consideration was also given to preventing outgassing of adhesives used in its construction. Adhesives were chosen from NASA 1124. To further prevent outgassing, the package was pressurized at 1.5 atmospheres with argon and hermetically sealed. Laser welding was utilized to minimize heat input and prevent distortion during sealing.

The upper portion of the package required a window transparent to ultraviolet light. This window was provided by a magnesium fluoride single crystal wafer. The window was sealed to the Invar body using iridium metal.

Contamination during assembly was found to be critical, even though the assembly was performed in a class 100 clean room. The small number of particles making it through the HEPA filters would acquire a charge which would cause them to stick to the device surfaces. Once in place, particles of only a few microns diameter would partially obscure the tiny pixels (15 microns) of the CCD. This would in turn limit the accuracy and resolution of the Hubble instrument. This problem was minimized by placing neutralizing grids on the air exhaust from the HEPA filters.

Example - The Deep Space 2 Mission

The Mars Microprobe will ride along on the Mars '98 spacecraft. It will be a separate, self contained mission which piggybacks on Mars '98 in order to get a convenient ride. It is a micro spacecraft, the entire body of which can be held in one hand.

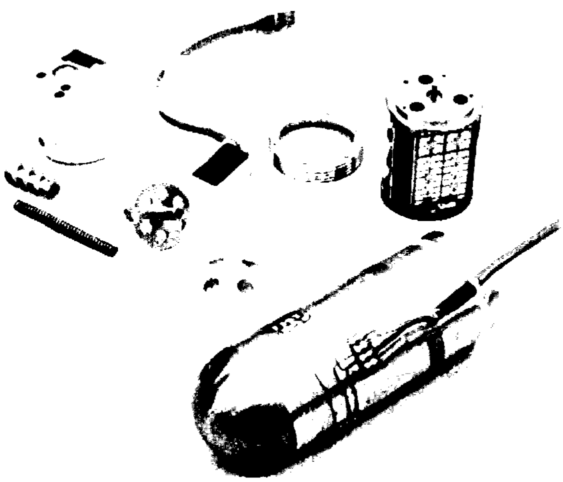

Fig 8. *Mars μProbe Forbody*

After separation in orbit around Mars, the microprobe will enter Mars' atmosphere and begin a freefall descent to the surface. It will collide with the Martian surface and separate into two sections, a penetrator which will go several feet under ground and an aft body which will remain on the surface. The penetrator will see a force of approximately 20,000 Gs while the aft body will see forces as high as 80,000 Gs.

A MEMS accelerometer will be located in the aft body while the penetrator will

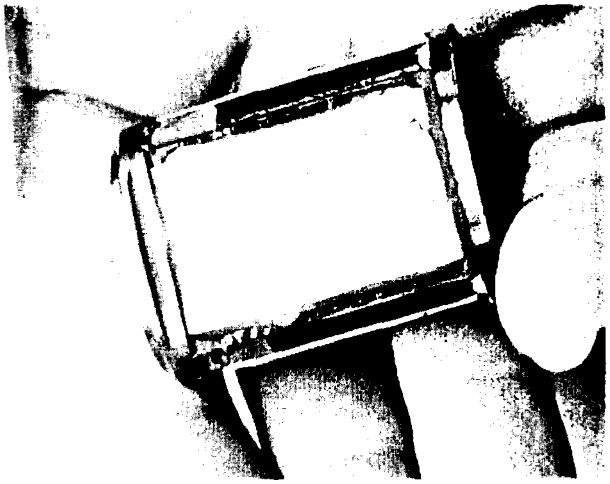

Fig 9 Closeup of DCA μElectronics Package

contain a tunable diode laser and an IR detector. The requirements for operation after high velocity planetary impact are unique and as such drive the packaging design to somewhat different approaches. For both subassemblies the general approach for packaging the electronics is to provide a high stiffness supporting structure upon which the multilayer substrates and their associated components are mounted. With this design approach the individual components need only **carry their inertial loads. The** predominant method for interconnecting the various subsystem substrates is with multilayer flexible circuitry.

Active components will be assembled directly onto the substrates using Chip on Board (COB) wire bonded assemblies. To minimize mass, and thus inertial loads upon impact, the chip to substrate bond wires will be aluminum.

The aftbody electronics substrates will be supported by the cover for the battery support cavities. The substrates will be fabricated from Low Temperature Cofired Ceramic (LTCC) with a wirebondable top layer metallization. Die containment cavities allow wirebonding with little strain relief loop. The interconnect between the substrates will be through polyimide film flex circuitry with surface mount solder lead attachment.

An external test and power connection will be provided through a metal bump compliant connector. In general the

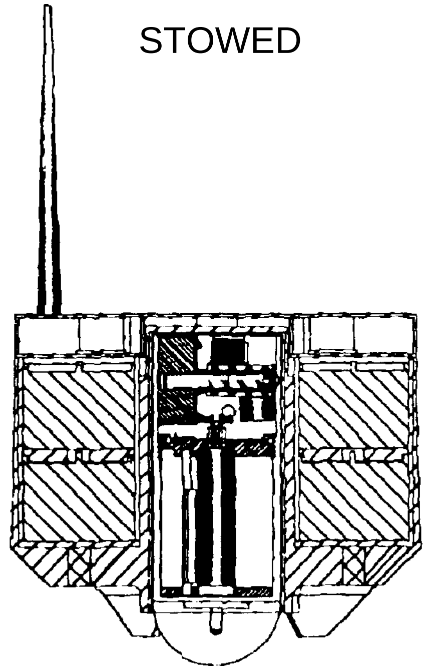

Fig *10. Mars μProbe X-Section In Flight (Stowed) Configuration*

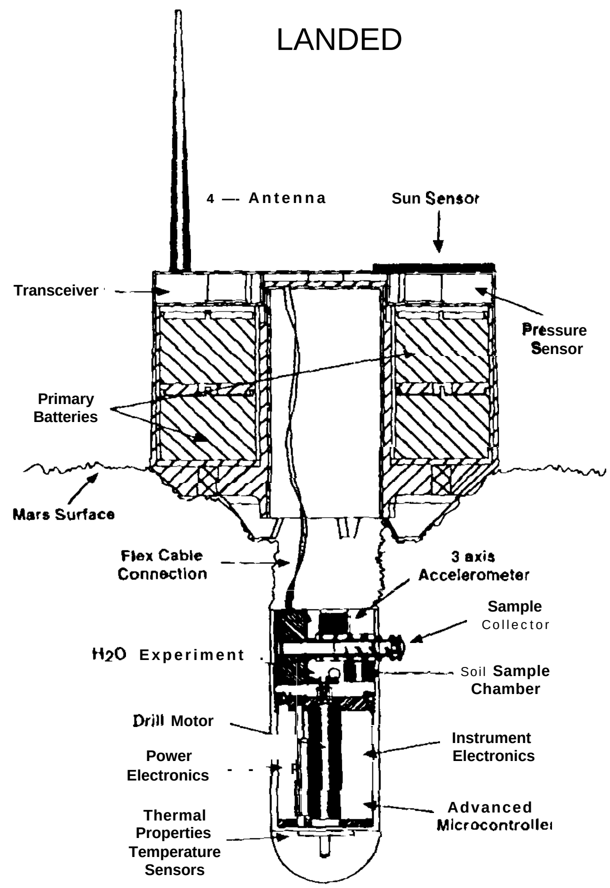

Fig 11. Mars μProbe Showing Separation of Fore and Aft body Sections After Landing (Stowed) Configuration

attachment of leads or discrete wiring from such components as the battery cel 1 stacks will be through surface mount solder joints. The Umbilical between the Microprobe Forebody and Aftbody will connect through the anisotropic adhesive/solder joint developed by Lockheed-Martin. This connection is made after insertion of the forebody into the aftbody central housing. The entire aftbody electronics assembly will be passivated with Silicon Nitride and protected by a non-hermetic cover. The connection between the communication electronics and the antenna will be through an impedance matching strip line.

Future work

NASA has recognized that in order to make optimal use of this new branch of technology, considerable effort will be necessary to develop qualification and inspection techniques, modeling methods and reliability assessment tools. A primary object is to form partnerships with industry and between NASA project areas which need to address problems generic to MEMS.

Work is underway to facilitate the use of process and product modeling for MEMS. Our eventual goal is not only to qualify specific MEMS devices for spaceflight but also to integrate the knowledge gained by ourselves and our industrial and project partners to produce a set of guidelines for the reliable design, fabrication and packaging of MEMS.

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